Is the Gaussian Channel Model Suitable for Converged Metro-Access Optical Networks?

(Article begins on next page)

Is the Gaussian Channel Model Suitable for Converged Metro-Access Optical Networks?

1st Andrea Rosso
DET, Politecnico di Torino
Turin, Italy
andrea.rosso@polito.it

2nd Enrico Miotto
DET, Politecnico di Torino
Turin, Italy
enrico.miotto@polito.it

3rd Emanuele Virgillito
DET, Politecnico di Torino
Turin, Italy

4th Stefano Straullu
LINKS Foundation
Turin, Italy

5th Vittorio Curri
DET, Politecnico di Torino
Turin, Italy

***Abstract*—We investigate the validity of the Gaussian channel model for converged metro-access optical networks, focusing on scenarios where dual-polarization coherent transmission extends across both metro and access segments. We demonstrate that, when appropriately defined, the model remains valid and is effectively characterized by amplified spontaneous emission noise from amplifiers and nonlinear interference from fiber propagation. However, in the context of single-fiber bidirectional propagation typically employed in access segments, additional impairments due to crosstalk and reflections must be considered as a distinct noise source. Furthermore, quality-of-transmission penalties arising from filtering and polarization-dependent loss can significantly impact performance and must be accounted for. To accurately capture the end-to-end system behavior, a realistic transceiver (TRX) model is essential, particularly to reflect the interplay between channel and TRX noise as a function of the received power—which may be low due to the passive nature of the access segment. Our results confirm that, with these considerations, the Gaussian channel model provides a robust and insightful framework for performance evaluation in converged optical networks.**

***Index Terms*—APN, ONaaS, 6G, DCX, Digital Twin**

I. Introduction

With the evolution toward All-Photonic Networks (APNs)—enabled by the transparent convergence of metro-access optical networks (CMAONs) through the removal of opaque interfaces—Optical Network-as-a-Service (ONaaS) is emerging as the most energy-efficient, high-capacity solution to support dynamic end-to-end data center exchanges (DCX), driven by AI and the massive traffic demands of O-RAN and 6G x-hauling. A key enabler for achieving optimized, low-energy, virtualized, and sliced network control is the development of an accurate physical-layer digital twin encompassing modeling of all relevant physical effects.

In this work, we introduce how the Gaussian channel model [1], extensively validated in core [2] and metro [3] network scenarios, can be effectively extended to CMAON scenarios, provided that specific effects are properly accounted for. These include the additional interference arising from reflections in access network segments exploiting bidirectional propagation, a transceiver (TRX) model that incorporates both the signal-to-noise ratio (SNR) and the received optical power (ROP), and the SNR penalties induced by filtering and polarization-dependent loss (PDL) mainly introduced by crossed reconfigurable optical add/drop multiplexers (ROADMs).

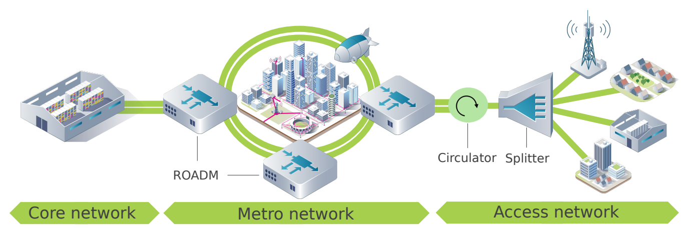


Fig. 1: Converged metro-access optical network architecture.

II. The Converged Metro-Access Scenario

Access optical networks are progressively evolving into a pervasive infrastructure that enables high-capacity Internet access for the majority of the population, based on Passive Optical Network (PON) standards [4]. These standards are designed for minimal spectral usage, typically relying on a passive optical tree architecture kept optically separated from other network segments. Such an infrastructure can be upgraded to transparently support Wavelength Division Multiplexing (WDM) traffic and be seamlessly integrated with metro networks through the introduction of a circulator (Fig. 1). This enables the transition from the conventional bidirectional fiber pair characteristic of metro networks to the single-fiber bidirectional infrastructure used in access networks. Without requiring additional capital expenditure (CAPEX) investments, the CMAON (see Fig. 1) can be exploited as a service for multiple use cases. For example, 6G x-hauling can leverage this infrastructure to connect radio units (RUs) to distributed units (DUs) and centralized units (CUs) within a metro network footprint [5]. Moreover, the CMAON can be effectively utilized for data center exchange (DCX) scenarios, enabling the interconnection of centralized and distributed data centers. This supports the progressive cloudification of services that demand high-capacity, low-latency data exchange, increasingly driven by AI applications. Such "as-a-service" use of the CMAON requires an accurate digital twin of the infrastructure, operated by an overarching metro-access controller, to ensure maximum capacity and

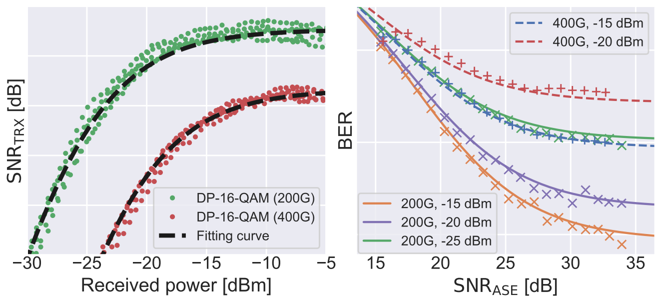


Fig. 2: Experimental characterization of transceiver.

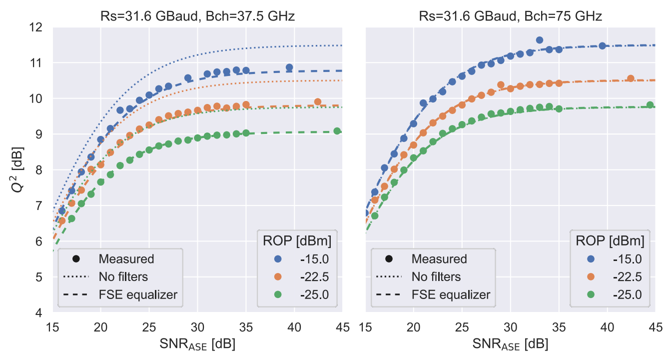


Fig. 3: Experimental validation of filtering penalty model based on realistic Fractionally Spaced Equalizer for three different ROPs.

minimum latency traffic deployment. At its core, the DT must include an accurate transmission model supported by appropriate interfaces, forming a time-varying digital shadow of the physical network.

III. Transceiver model

A critical impairment in optical communication lines is caused by electrical noise introduced by transceivers. For every lightpath it is possible to consider an SNR contribution $\mathrm{SNR}_{\mathrm{TRX}}^{-1} = \mathrm{SNR}_{\mathrm{TX}}^{-1} + \mathrm{SNR}_{\mathrm{RX}}^{-1}$ that depends jointly on the performances of the transmitter and the ones of the receiver. However, for practical use cases, it is possible to assume the former to be constant and negligible in respect to the latter, which in turn is strongly dependent on the received power value. For this reason, a characterization can be performed in a back-to-back (B2B) configuration using a Variable Optical Attenuator (VOA) to test the transceiver's performances at different power levels [6]. To obtain the $\mathrm{SNR}_{\mathrm{TRX}}$ from experimental BER measurements, the equation $\mathrm{BER} = k_1 \cdot \mathrm{erfc}\left(\sqrt{k_2 \cdot \mathrm{SNR}}\right)$ is inverted, considering the transceiver as the only noise source, and k_1 and k_2 depending on the modulation format [7].

The obtained characterization can then be used to compute the $\mathrm{SNR}_{\mathrm{TRX}}$ at every received power, and can be used in conjunction with the SNR of the line to accurately predict network performance [8]. The transceiver effect is especially relevant in CMAONs where the received power can reach very low values due to the presence of several passive components in the access segments.

IV. The Gaussian Channel model

In this section, we discuss how the Gaussian channel model—where the decision signal after equalization is affected by additive Gaussian noise—can be effectively extended to CMAON scenarios using dual-polarization coherent TRXs. All noise sources must be properly accounted for to accurately define the signal-to-noise ratio (SNR) required by the TRX model, along with the ROP assessment. Additionally, the penalties introduced by ROADMs, including filtering and polarization-dependent loss (PDL), must be considered, as they collectively define the overall Gaussian channel penalties.

A. Noise Sources

In CMAON scenarios, beyond the noise generated by amplifiers—namely, amplified spontaneous emission (ASE) noise—and the nonlinear interference (NLI) introduced by WDM fiber propagation [9], which define the $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$, additional noise sources must be considered. These include crosstalk from ROADMs—both from side channels and residual dropped channels, contributing to the $\mathrm{SNR}_{\mathrm{XT}}$—as well as interference from reflections caused by bidirectional transmission, which define the $\mathrm{SNR}_{\mathrm{BiDi}}$ when the same wavelength is used for both upstream and downstream traffic [10]. Reflections can originate from lumped sources (such as form connectors, splices, splitters, and circulators) or from distributed Rayleigh scattering. Since these interferences arise from linear crosstalk mechanisms, they can be modeled as Gaussian random processes. Furthermore, while access segments do not introduce significant additional noise beyond reflections, it is crucial to account for the substantial signal loss, as this directly affects the impact of TRX noise, as described in Section III.

B. Filtering Penalty

A notable impairment in optical links is due to the presence of optical filters, which alter the shape of signals passing through them. In practical scenarios, this effect is introduced by wavelength selective switches (WSS) incorporated into ROADMs that implement optical filters to route the lightpaths in the optical domain.

When a signal is filtered, its shape is distorted, and thus it must be reconstructed by an equalizer, that is typically implemented digitally inside the receiver. However, in presence of noise sources located after the filters, when the equalizer tries to recover the channel response, it causes an unwanted distortion of the noise, which becomes enhanced. Additionally, supposing the noise sources to be white, they also become colored, and this effects must be taken into account while predicting the overall network performances.

The most general condition is obtained by considering a cascade of filtering elements and noise sources, which is typical of metro and access networks, characterized by a sequence of ROADMs and amplifiers, possibly with single sided filtering [11] or frequency shifts [12].

A study of the different contributions considered independently highlights the importance of the position of the noise sources along the line: in particular, a noise located closer to the receiver impacts more the overall performances because it is the one characterized by the most different filtering condition with respect to the transmitted signal, and so it is also the one to which the largest distortion is applied by the equalizer. In particular, since the noise introduced by the receiver is always the last contribution in the line, it becomes relevant to properly and accurately characterize the transceiver performances as presented in Section III.

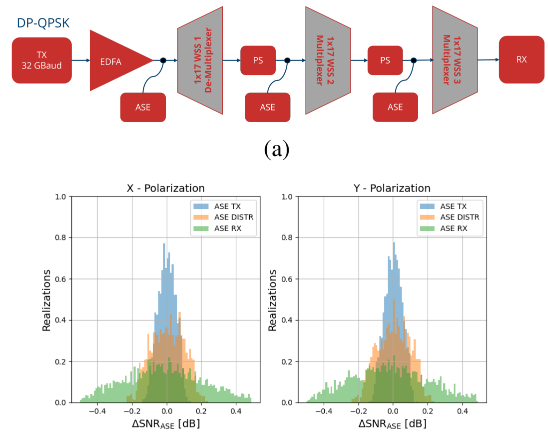
A practical example is presented in Figure 3: four noise sources are arranged in sequence, with three filters in between them. The noise sources can be controlled in order to provide the same $\mathrm{SNR_{ASE}}$ contributions, and the filters are configured with the same bandwidth and the same central frequency as the channel under test. As it is possible to observe, even when the filters are not very tight (37.5 GHz on a 31.6 GBaud signal), the introduced penalty is not negligible, and the experimental data points show a reduction in the Q factor with respect to the condition in absence of filters. The Q factor is computed according to $Q = \sqrt{2} \cdot \mathrm{erfcinv}(2 \cdot \mathrm{BER})$, possibly converted in logarithmic scale as $Q^2_{dB} = 10 \cdot \log_{10}(Q^2)$. However, this effect can be accurately predicted by considering the equalizer model: several models can be used, with the Fractionally Spaced Equalizer being the most realistic one in respect to the real transceiver implementations [13]. As it is possible to see in Figure 3, even assuming infinite taps, FSE is able to provide a very good prediction of the experimental data. Alternatively, [14] shows a different model based on the Zero Forcing Equalizer (ZFE) in which every filtering penalty contribution depends only on the shape and position of the filters. This approximation introduces a small additional penalty while always keeping the prediction conservative, but the fact that the model is independent on the SNR values along the line allows to obtain a fully disaggregated model, which is a notable advantage when implementing a network digital twin, as shown in Section V. In all the considered cases, the dependence on the ROP is fully accounted for in the transceiver model.

C. PDL penalty

In addition to filtering penalty, the WSSs leveraged by ROADMs are responsible for introducing PDL. Being time, frequency [15] and port [16] dependent, PDL impacts on system performance causing SNR fluctuations over time. Metro-access optical networks are characterized by the presence of many cascaded ROADMs, with distributed ASE noise injection due to optical amplification. Moreover, metro-access networks are exposed to temperature cycles, and mechanical stresses due to traffic vibrations, which cause random polarization rotations. Such scenario makes the PDL penalty on SNR significant, and randomly varying over time. We focus on the penalty on $\mathrm{SNR_{ASE}}$, since similar considerations can be applied to the other noise sources listed in Sec. IV-A.

As what happens for filtering penalty, PDL-induced $\mathrm{SNR_{ASE}}$ distributions depend on the reciprocal position of PDL and ASE noise injection along the optical link [17]. This happens because PDL occurs on signal and noise depending on the number of crossed WSSs, therefore noise experience a different amount of PDL compared to the transmitted signal. Such phenomena is exemplified in Fig. 4b, where the $\mathrm{SNR_{ASE}}$ distributions (for both the main polarization relatives) have been experimentally obtained from the setup in Fig. 4a. ASE noise has been injected according to three possibilities: all at transmitter side (ASE TX), all at receiver side (ASE RX) and distributed along the line in order to have same $\mathrm{SNR_{ASE}}$ in each ASE injection point (ASE DISTR). A key observation is that the distributions are wider when ASE noise is concentrated at receiver side. This leads to a deterioration in performance, as extreme below-average $\mathrm{SNR_{ASE}}$ realizations are more likely to occur. Regarding the bell shape of the distributions depicted in Fig. 4b, it is possible to characterize the PDL-induced $\mathrm{SNR_{ASE}}$ distribution by a truncated Gaussian distribution. This choice is in accordance to both theory [18], [19] and experiments [15], [17].

In order to account for PDL penalty in the transmission model, performing system margin assessment, there is the need to express the standard deviation of PDL-induced $\mathrm{SNR_{ASE}}$ distribution in disaggregated and closed form. Knowing the standard deviation of the truncated Gaussian distribution, it is possible to compute a margin based on the desired out of service probability as in [15]. In [20], the following formula is proposed:



(b)

Fig. 4: (a) Experimental setup for PDL-induced $\mathrm{SNR_{ASE}}$ distribution measurement; (b) Experimental PDL-induced $\mathrm{SNR_{ASE}}$ distributions.

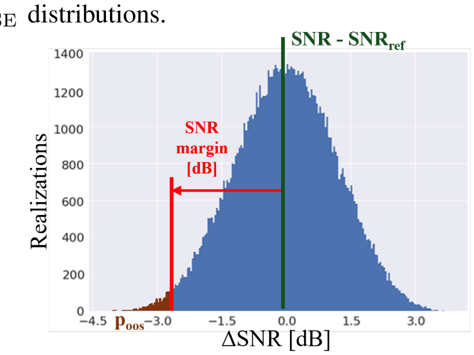


Fig. 5: System margin assessment on SNR distribution based on the maximum out of service probability $\mathrm{p_{OOS}}$.

$$\sigma = \mu \sqrt{\sum_{i,j=1}^{n_s} \left(\frac{N_i}{\mu_{s,i}^2} \frac{N_j}{\mu_{s,j}^2} \sigma_{s,i} \sigma_{s,j} \right)} \quad (1)$$

Where μ is the nominal $\mathrm{SNR_{ASE}}$ considering no PDL in the system, n_s is the number of PDL elements along the link, N_i is the ASE noise power of the source at position i, $\sigma_{s,i}$ and $\mu_{s,i}$ are the standard deviation and the average of the signal power at position i, where $i = 1, \ldots, n_s$. $\sigma_{s,i}$ and $\mu_{s,i}$ are directly influenced by the PDL value of each WSS.

The margin on the $\mathrm{SNR_{ASE}}$ computed after determining the standard deviation of the $\mathrm{SNR_{ASE}}$ distribution gives a statistical penalty assessment of $\mathrm{SNR_{ASE}}$ degradation. Such penalty quantifies how much PDL impacts on the system performance, and it can be represented by an opportune coefficient, as mentioned in previous section on filtering penalty. Then, the interplay of PDL and filtering effect can be summarized by opportune coefficients, as it will be clarified in next section.

V. The Digital Twin for Metro-Access Scenarios

In these scenarios, the digital twin must reliably evaluate three key metrics: the light latency, given by $\Delta T = 1.5/c\ L_{\text{prop}}$ [s]; the ROP, *ROP* $= P_{\text{ROADM}} - L_{\text{access}}$ [dB]; and the overall signal-to-noise ratio (SNR), used in the TRX model to estimate the bit error rate (BER) and consequently enable path feasibility computation. The first two metrics can be accurately evaluated using only the path propagation length L_{prop}, the ROADM output power P_{ROADM}, and the access loss L_{access}. In contrast, computing the SNR requires an accurate digital shadow of the overall infrastructure, as it is generally given by the following expression:

$$\mathrm{SNR}^{-1} = \frac{k_{\mathrm{ASE}}}{\mathrm{SNR_{ASE}}} + \frac{k_{\mathrm{NLI}}}{\mathrm{SNR_{NLI}}} + \frac{k_{\mathrm{XT}}}{\mathrm{SNR_{XT}}} + \frac{k_{\mathrm{BiDi}}}{\mathrm{SNR_{BiDi}}} + \frac{k_{\mathrm{TRX}}}{\mathrm{SNR_{TRX}}}. \quad (2)$$

The computation of each SNR term requires precise models of all network elements traversed by the path under test, including fibers, as well as information on the spectral load, WDM configuration, and channel spectra. The coefficients k account for the filtering effects along the path. The *BiDi* and *TRX* noise components are added after all filtering stages. The filtering impact on the *XT* and *NLI* terms is not yet fully understood; thus, a conservative approach assumes that also these two noise sources are added after all filtering stages, experimenting the highest possible penalty. Conversely, the filtering effect on the dominant noise source—ASE noise—has been theoretically clarified in [13], and a precise assessment is feasible, provided the exact locations of noise generation and filtering are known. Another crucial factor to consider is that k must be considered as statistical values due to the PDL effect depicted in Section IV-C. Since filtering effect is deterministic, the expected value of each k is the result of the interplay of filtering penalty and PDL, while its pdf is PDL-dependent. This lead to the possibility of determining the system margin on the SNR statistic, as represented in Fig. 5.

In summary, a digital twin based on the Gaussian channel model can be developed for CMAON scenarios. A reliable digital shadow of the network is essential for enhancing the digital twin's accuracy, thereby enabling the maximization of deployed capacity and the minimization of energy consumption, expressed in Joule/bit.

VI. Conclusion

We have addressed the problem of channel modeling in converged metro-access scenarios, showing that the Gaussian channel assumption holds provided that additional noise sources, such as reflections, are considered alongside the crucial parameter of ROP. This modeling approach enables the development of an accurate digital twin, as long as precise knowledge of the infrastructure is available. Furthermore, we have highlighted how the QoT acquires a statistical nature, primarily due to PDL. Therefore, it is essential to have an accurate understanding of the network to deploy appropriate margins based on the maximum allowed outage probability.

Acknowledgements

This work has been partially funded by the EU — Next Generation EU under the Italian NRRP, Mission 4, Component 2, Investment 1.3, CUP E13C22001870001, partnership on "Telecommunications of the Future" (PE00000001 — program "RESTART") and by the Telecom Infraproject.

References

[1] V. Curri, "Gnpy model of the physical layer for open and disaggregated optical networking," *JOCN*, 2022.

[2] A. Ferrari *et al.*, "Softwarized optical transport qot in production optical network: a brownfield validation," in *2020 European Conference on Optical Communications (ECOC)*, 2020, pp. 1–4.

[3] A. D'Amico *et al.*, "Gnpy experimental validation in a c+l multiband optical multiplex section," in *2024 24th International Conference on Transparent Optical Networks (ICTON)*, 2024, pp. 1–4.

[4] J. S. Wey, "The outlook for pon standardization: A tutorial," *JLT*, 2020.

[5] A. Larraáaga *et al.*, "Fronthaul/midhaul networks: Capacity and latency requirements imposed by 6g disaggregated rans," *IEEE Communications Magazine*, 2025.

[6] T. Mano *et al.*, "Modeling the input power dependency of transceiver ber-onsr for qot estimation," in *2024 OFC*, 2024.

[7] Proakis, *Digital Communications 5th Edition*. McGraw Hill, 2007.

[8] A. Rosso, "Modeling and controlling optical transponder white-boxes based on the physical layer digital twin," Master's thesis, Politecnico di Torino, 2024.

[9] P. Poggiolini *et al.*, "The gn-model of fiber non-linear propagation and its applications," *JLT*, 2014.

[10] E. Virgillito *et al.*, "Propagation impairment in single-wavelength, single-fiber bidirectional optical transmission," in *Optica Advanced Photonics Congress*. Optica Publishing Group, 2022.

[11] Virgillito, Emanuele *et al.*, "Observation and modeling of filtering penalties in optical switched networks," in *ICTON*, 2024.

[12] Y. Sakamaki *et al.*, "Evaluation of optical filtering penalty in digital coherent detection system," *IEICE Communications Express*, 2012.

[13] E. Miotto *et al.*, "Introducing combined effects of filtering and ase noise in optical links supposing different equalization algorithms," 2025. [Online]. Available: https://arxiv.org/abs/2504.17408

[14] A. Rosso *et al.*, "Encompassing filtering effects in transceiver models for converged metro-access networks," in *ONDM*, 2025.

[15] E. Miotto *et al.*, "Statistical assessment of system margin in metro networks impaired by pdl," in *OFC*, 2025.

[16] A. D'Amico *et al.*, "Statistical analysis of pdl penalty on coherent transmission technologies based on wss experimental characterization," in *ACP*, 2022.

[17] D'Amico, Andrea *et al.*, "Experimental probing and modeling of the pdl impact on the optical signal-to-noise ratio," in *OFC*, 2023.

[18] A. Mecozzi *et al.*, "Signal-to-noise-ratio degradation caused by polarization-dependent loss and the effect of dynamic gain equalization," *JLT*, 2004.

[19] L. E. Nelson *et al.*, "Statistics of polarization dependent loss in an installed long-haul wdm system," *Opt. Express*, 2011.

[20] A. D'Amico *et al.*, "Disaggregated statistical characterization of the pdl impairment on the optical signal-to-noise ratio," in *PSC*, 2023.